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Technical Report

UNDERSEA NUCLEAR POWER -- A STATUS REPORT

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NAVAL FACILITIES ENGINEERING COMMAND

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UNDERSEA NUCLEAR POWER — A STATUS REPORT

Technical Report R-470

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by

E. J. Beck

ABSTRACT

Since the publication in 1964 of Techniques for Underwater Nuclear Power (NCEL TN-545), considerable research and development has been done which has changed the picture regarding the feasibility of using isolated reactors on the ocean bottom. This study considers in some detail the work on fouling, corrosion, and heat transfer accomplished by the C. F. Braun Company, Alhambra, California, under contract NBy-32274.

Also considered are additional problems which might be encountered in using radioisotope decay heat in large (multi-kilowatt) generators or fuel cells in the deep ocean environment.

A cursory up-dating of the known arts related in the earlier study is made, especially in referencing material which has recently become available.

Possible areas for further investigation are delineated.

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The Laboratory invites comment on this report, particularly on the results obtained by those who have applied the information.

INTRODUCTION

The purpose of this report is to update a similar study, Beck et al (1964) prepared in 1963. In particular, the updating is done with respect to heat transfer, fouling, and corrosion of warmed surfaces. The earlier study consisted of 10 chapters, the last of which specified particular problems in need of investigation. This study summarizes progress to date and shows the continuing need for research and development. The 1963 study emphasized the problems in placing and monitoring unattended nuclear-power plants; the results are applicable to any underwater power source of any size or to any structure losing heat to the ocean.

Many of the problems which would inhibit the production of subsurface power have been under intensive investigation. The significant uncertainties were stated as follows: (Numbers are those of chapters of the reference)

I. The environment

II. Fouling

III. Corrosion

IV. Foundations on ocean floor

V. Anchorage

VI. Placement & recovery

VII. Underwater vision

VIII. Heat rejection

IX. Nuclear contamination of the oceans

X. Location & relocation, position holding

Connection to power source

Service vehicles & manipulating

Reactor monitoring

Ocean currents

Temporary power storage

The remainder of this report will deal with the status of knowledge in the listed areas, especially with the progress in cooling by free convection and with the fouling and corrosion of selected warmed surfaces exposed to various depths of water near the ocean's bottom.

The survey of recent work in most areas is far less specific and comprehensive than in the area of heat transfer and fouling; these areas will be discussed in the appendix, which should not be considered as representing the limit of progress.

DISCUSSION

Change in Concept of Undersea Power

At the beginning of the investigation of undersea power, it was conceived that early placement of a medium-sized reactor would be desirable and that problems relating to such a reactor would require early solutions. (Beck et al, 1964.) It now appears that other, and probably smaller, submerged power sources will be of interest as well. A reactor generating 20 to 3,000 kw of power using a relatively inefficient cycle still appears to be the worst situation likely to be met. However, the discussion and most of the solutions are intentionally generalized to include the less demanding problems of smaller sources, as they are known at this time.

PROBLEMS RECENTLY SOLVED

Status of Reactor Placement and Retrieval

Specific studies have been done to solve many of the problems in the placement and operation of power-generating devices in remote, unattended deep ocean sites.

A major study (Bechtel, 1965) was made of the methods of placement, monitoring, and retrieval of a heavy reactor in very deep water. The principal approach studied was the carrying of the reactor in a special well in a modified ship (tanker) and lowering it at the site with pressure-resistant buoyancy materials. Two systems were analyzed: one required the use of a small submarine for guidance and control; the other allowed lowering to be done with control entirely from the surface. Because no experimental work was done, the system was not really demonstrated. However, a simple model which is used to illustrate the methods developed was constructed. The work was described by Quirk.*

It is probably fair to conclude that sufficient care was taken in the analysis to allow confidence in a successful placement of the reactor. However, the dynamic aspects of handling large weights at great depths by elastic cables do not appear to

*Quirk, J. T. Deep ocean placement studies. U. S. Naval Civil Engineering Laboratory, Port Hueneme, Calif., (Unpublished TN-656), and Quirk, J. T. and Muga, B. J. Pullout forces in ocean bottom muds. U. S. Naval Civil Engineering Laboratory, Port Hueneme, Calif., (Unpublished).

be well demonstrated. Before a reactor is placed, it appears prudent to demonstrate the final technique to be used to insure its practicability and safety. Some consideration should probably be given to designing sufficient bouyancy into the reactor's shield to allow the device to be towed to the placement site rather than carried, because modification of the proposed tanker was a major part of the projected cost, and removing the reactor from the well was a major handling problem.

Status of Fouling and Corrosion

At the time the following experiments were undertaken, there was no known similar work on heated surfaces. In fact, it is only within the last few years that systematic exposure of unheated materials to deep ocean environments have been made. Observations of retrieved materials accidentally sunk were restricted mainly to items recovered from a few hundred feet deep because of the problems in locating and retrieving items from greater depths.

The early observations of numerous unheated specimens exposed at deep ocean sites have been described in great detail by Muraoka (1964; 1965a,b,c) and Reinhart (1964, 1965, 1966).

The first known definite observations of heated specimens exposed at great depths were reported in Braun (1965). Tests of copper nickel alloys with surface temperatures in shallow harbor water of 100, 120, and 140°F and at depths of 300 feet and 4,700 feet in the open ocean indicated that neither fouling nor corrosion would be a problem on heated surfaces. However, fouling on adjacent unheated surfaces was accelerated, which might be expected because of the slightly warmer water. From a design standpoint, it would be important to avoid configurations in which rising warm water could promote fouling, which could in turn interfere with the circulation necessary for cooling. An experiment on the fouling of nonheated parts above the heat-rejection surface is shown in Figure 1 (from Braun, 1965). The observed corrosion would be important only after very long exposure and if it were progressive. This was not determined.

The effectiveness of even moderately and intermittently heated seawater in inhibiting marine growth is illustrated by a recent report of an industrial application (Bladholm, 1966). Circulating pumps at a Southern California electric plant are reportedly effectively cleaned (or at least, the attached slime and organisms are killed) by periodically circulating seawater at 105°F in the pumps. In the situation illustrated in Figure 1, the circulation rate over the specimens was high enough that the water was only slightly warmed; as a result, the heated surfaces were essentially kept clean, but the adjacent supporting parts were not.

Results of corrosion tests as reported in Braun (1965) can be summarized briefly. Several alloys known to have good resistance in the sea environment were exposed at the three test temperatures: 100, 120, and 140°F. Of the candidate materials, 90:10 cupronickel proved best, with 70:30 cupronickel acceptable. Aluminum bronze showed a tendency toward losing aluminum in the tests at 4,500 feet, but the results were not considered conclusive. Typical specimen conditions after test are illustrated in Figure 2 (from Braun, 1965).

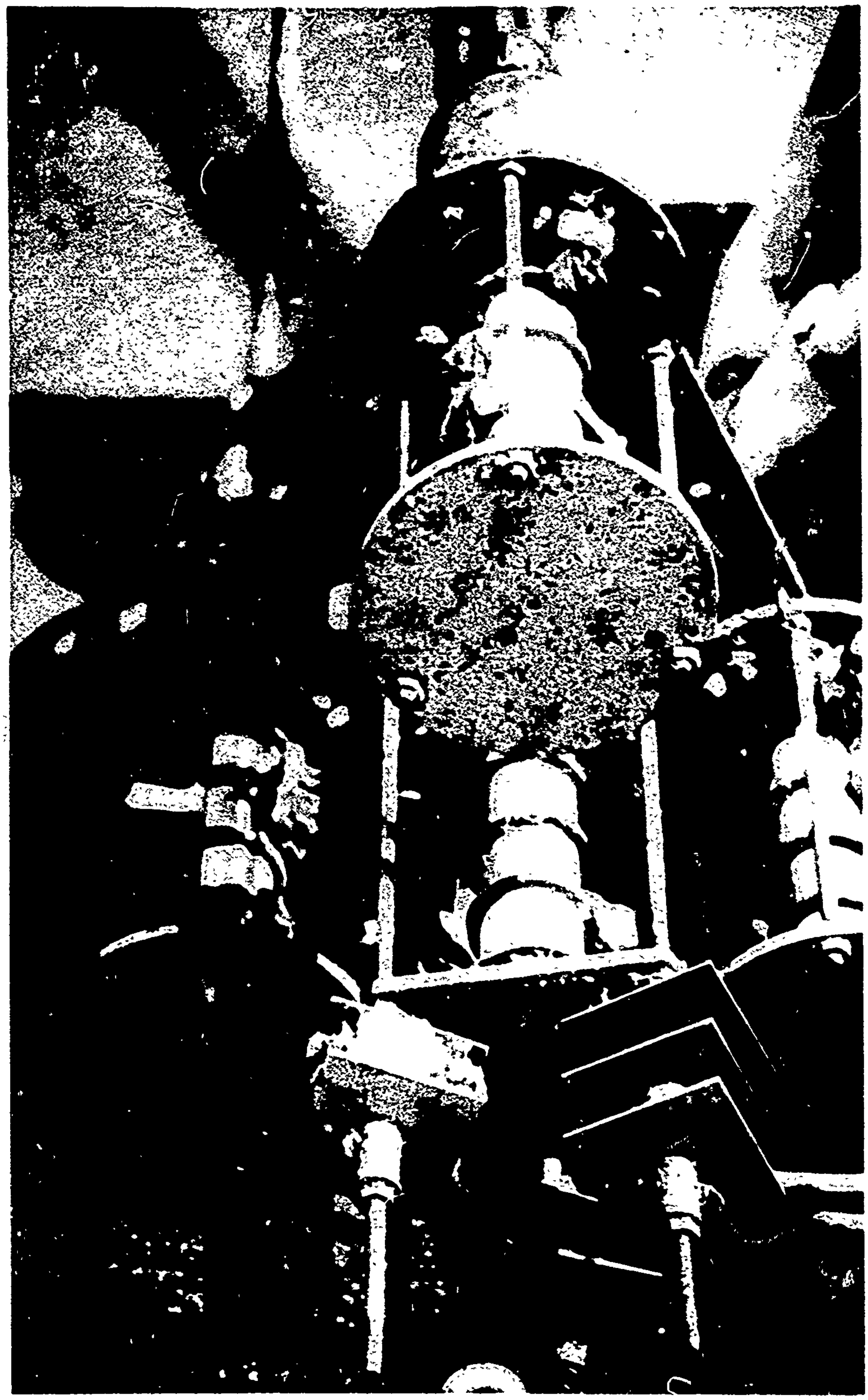
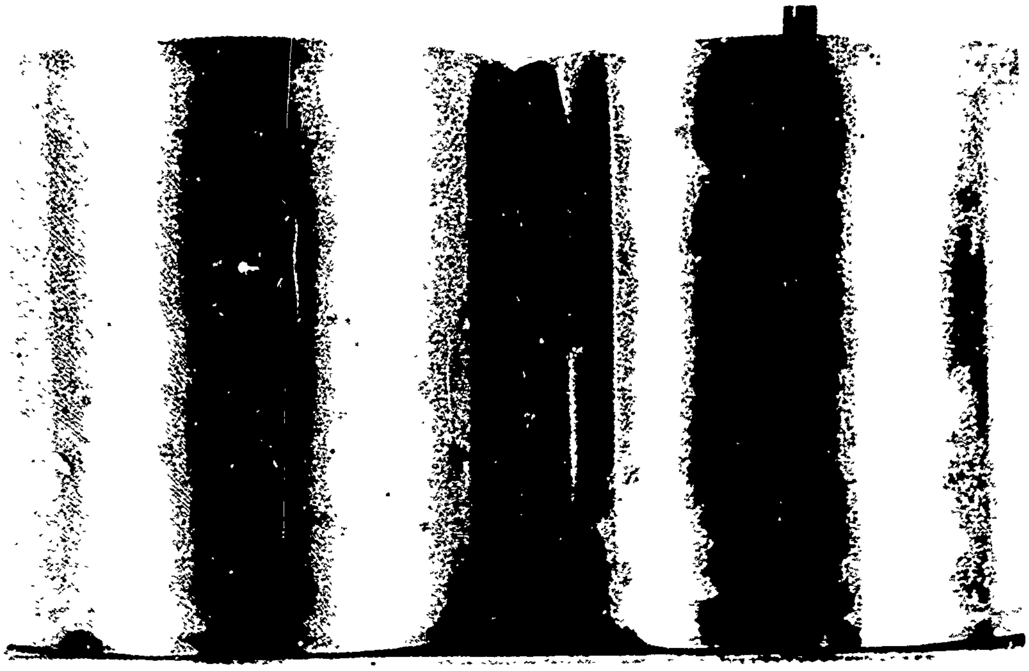
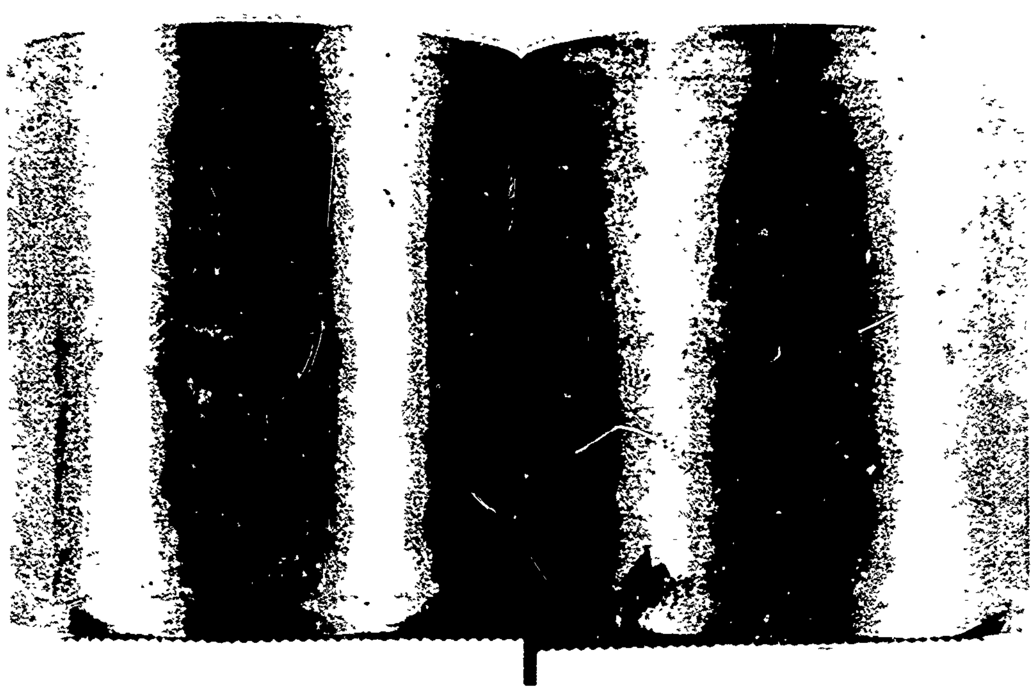


Figure 1. Overall view of test unit showing fouling of unheated surfaces.



Monel — Cold Monel — 100°F

(a)



70:30 Cu Ni — Cold 70:30 Cu Ni — 100°F

(b)

Figure 2. Appearance of (a) monel and (b) 70:30 copper nickel after the 4,500-foot test.

It was impractical because of cost limitations to conduct fouling and corrosion tests for long periods in the very deep ocean. Tests were run for months in a shallow protected harbor, a week in open water a few hundred feet deep, and a few days at a 4,500-foot depth. By close observation of the decay in the heat-transfer coefficients from the electrically heated specimens (as calculated from changing surface temperatures at constant heat input), it was determined that the initial rate of coefficient decay was essentially the same for all cases. The logical but not necessarily defensible conclusion at this point is that fouling is similar for all depths for heated surfaces which inherently inhibit fouling. Nevertheless, there is some chance that with widely varying bottom conditions, controversial findings may be obtained if long-time rejection of heat occurs in major equipment.

Long-time exposure with controlled surface heating appears to be impracticable. However, much experience in exposing sizeable thermoelectric generators using radioisotope decay heat (SNAP) for powering instruments and experience in rejecting heat from radioactive decay may shed light on the problem in the near future.

Dissipation of a Rising Plume

The upwelling of a plume of heated water over a large reactor rejecting copious quantities of heat was seen as a potential problem if the plume should penetrate the ocean's surface, causing a hot spot. Some background in connection with this problem was given (Beck et al, 1964), and a detailed study was made as part of the C. F. Braun Company's study (Braun, 1965). The problem is well understood intuitively by anyone who has observed the expansion and dissipation of a rising column of heated smoke from a chimney on a still day. Mathematically, the phenomenon was previously of interest primarily in connection with mass fires and the special cases of a rising cloud from an atomic weapon blast (e.g., Taylor, 1961 and 1945). Taylor (1947) used laboratory experiments with density-layered liquids to allow investigation under controlled conditions.

Braun (1965) treats the overall subject in great detail, and a mathematical model of a plume is compared with the results of experiments both in the laboratory and in a free-convection experiment dissipating 50 kw in a harbor. The plume is effectively dissipated at whatever height is required to reduce its temperature (and at the same time its bouyancy) until it is essentially equal to the ambient temperature. The rising jet entrains cool fluid by momentum exchange. Without this dilution by entrainment, there would still be a quenching effect because of the expansion, which would be essentially adiabadic with loss in pressure. Because water is relatively much less compressible than air, the quenching effect is much more pronounced in the latter. Nevertheless, the effect could be important for deep water. To avoid a brief presentation which might indicate a deceptively simple solution, reference is made to the original Braun text for a comprehensive treatment.

In summary, it appears that for any reasonable depth of submergence and with even very small lateral currents, the plume of heated water would normally be effectively quenched well below the surface. In fact, very slow currents occurring during the harbor tests were so effective in wiping out the plume that the warming could be studied only at a change in tides.

Rejection of Heat Transfer by Natural Convection

Much of the world's heat is rejected to the atmosphere by natural convection at least part of the time, but it is largely unplanned. Typically, it is uneconomical to transfer large quantities of heat in industrial processes by natural convection, and the process of heat transfer is hastened with the aid of fans, pumps, and the introduction of cold, dense fluids from wells, streams, etc. The heat-transfer process usually used is forced convection. With significant wind, radiation, or wet-film evaporation, heat loss by pure natural convection becomes a trivial effect. There is a notable exception. Air-cooled electrical transformers frequently are designed for natural convection. The loss per unit area needed for cooling is relatively small, and the transformers' size and shape allows successful cooling. Cooling design suitable to this application is an exception to the general situation in convection cooling; specialized design techniques have not been developed in this field. For the application cited, Starner and McManus (1963) did a useful investigation. Another specialized and interesting application is described by Noronha (19[illegible]4) in the cooling of cabinets for electronic devices.

Traditionally, design problems in natural convection have been handled by rather simple equations based on dimensional analysis:

$$Nu = C\,(Ra)^{1/4} \qquad (1)$$

For a discussion of this and other simplified approaches, see Beck et al (1964). It was recognized early in the progress of this study that the dense, cold waters of the deep ocean would offer significant opportunity for simple, economical rejection of heat from suitable convection surfaces without resorting to expensive and complicated pumps and that the heated water would rapidly dissipate. However, it was also seen that design methods would probably be inadequate. Further investigation showed that known applications were all to gases, at relatively low Rayleigh numbers. This investigation was the basis for further study: to develop reliable design methods for the deep ocean. The resulring study, reported in Braun (1965), brought out the inadequacy of the existing research data in the range of Rayleigh numbers covered, especially the lack of agreement between the research results reported, which were largely for laminar flow. At higher heat-rejection rates, turbulent flow could be expected. The best information available at Rayleigh numbers over 10^9 is shown in

Figure 3 (from Braun, 1965), where both the experimental methods and resulting correlating equations are discussed in some detail. The approximate equation was usually of the order:

$$Nu = C\,(Ra)^{1/3} \tag{2}$$

However, somewhat better fits could be obtained by adding $Pr^{(n)}$ as an additional factor on the right side. The exponent might be positive or negative and appear in different situations depending on the data used and the values assigned to the coefficient, C. The Braun tests for the simple case of the vertical flat plate justified the adoption of Saunders' equation:

$$Nu = 0.17\,(Ra)^{1/3} \tag{3}$$

The data are plotted in Figure 4. The relationships of interest in more complex surfaces, however, such as that in Figure 5, are not so simple, and considerable care must be used to optimize such a design. Braun (1965) devotes a section to design procedures, and gives numerous design aids (for example, Figure 5) for use in optimizing fin spacing.

Perhaps the most noteworthy aspect of the designs arrived at by the method developed in Braun is illustrated by the test units shown in Figure 6. The fin spacing and thickness and height are all atypical of what might have been arrived at for a design for laminar flow with heat transfer to a gas. The fin spacing is dictated by boundary-layer thickness, and the thickness of the fins is determined by the relatively high heat-transfer coefficients, which would require a heavy metal section for transmitting the large amounts of heat without excessive temperature drop. The fins shown are of copper and are thick in spite of copper's high thermal conductivity; steel, for instance, would require fins that were relatively thicker and not so tall (normal to the heated surface).

The results of the theoretical analysis and laboratory experiments described briefly above were incorporated into what was considered a near-optimum arrangement for a unit of the type shown in Figure 7, and this unit was tested in the laboratory and in the Port Hueneme Harbor. The test results verified the reliability of the design.

Other aspects of convector design were covered; for example, the effect of restricting entrance area at the bottom of the convector and providing increased flow by superimposition of a chimney. It is believed that the work is sufficiently comprehensive so that the probable effects of most novel design arrangements can be deduced from a careful study of the report. Heat-transfer problems appear to be solved.

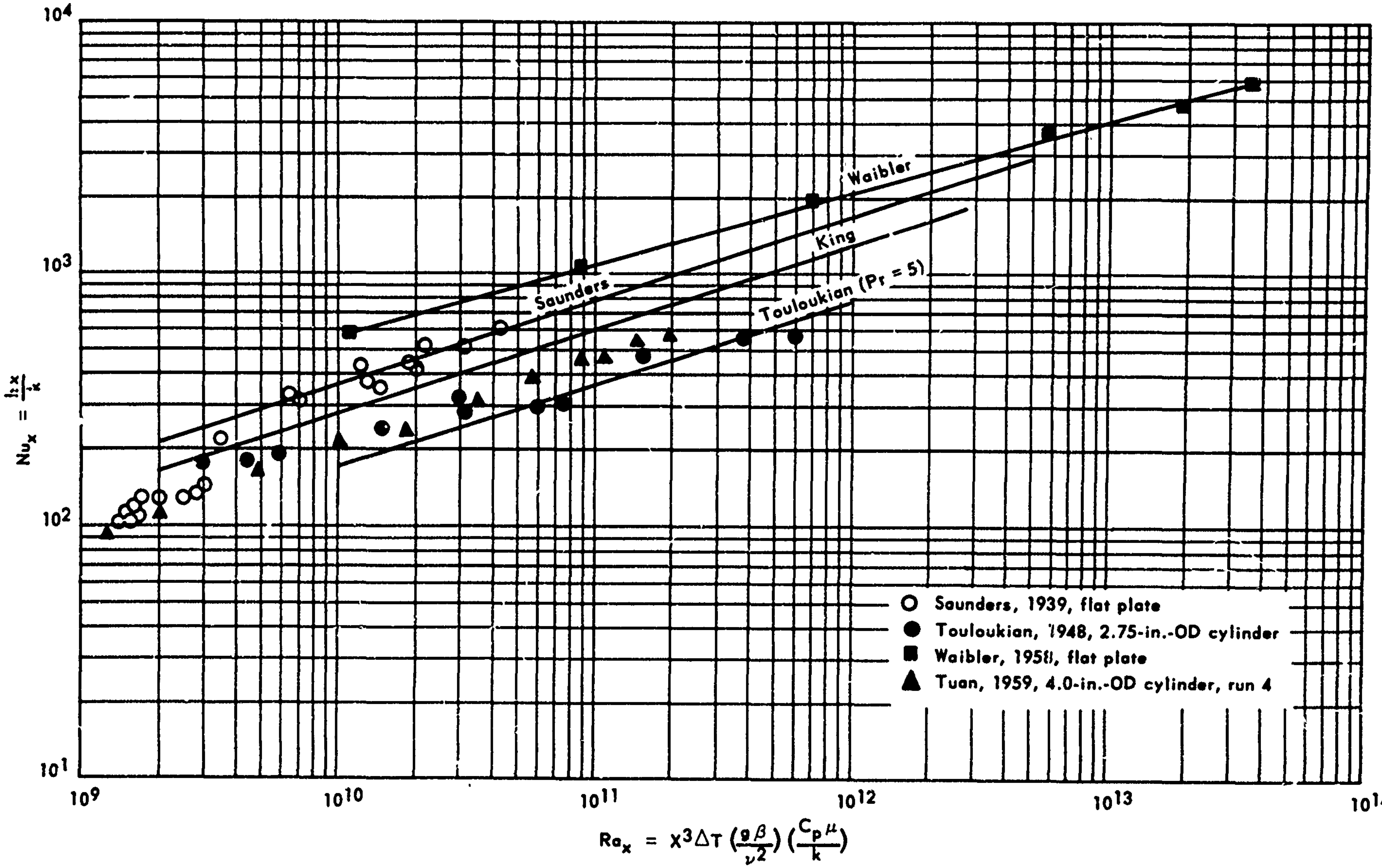
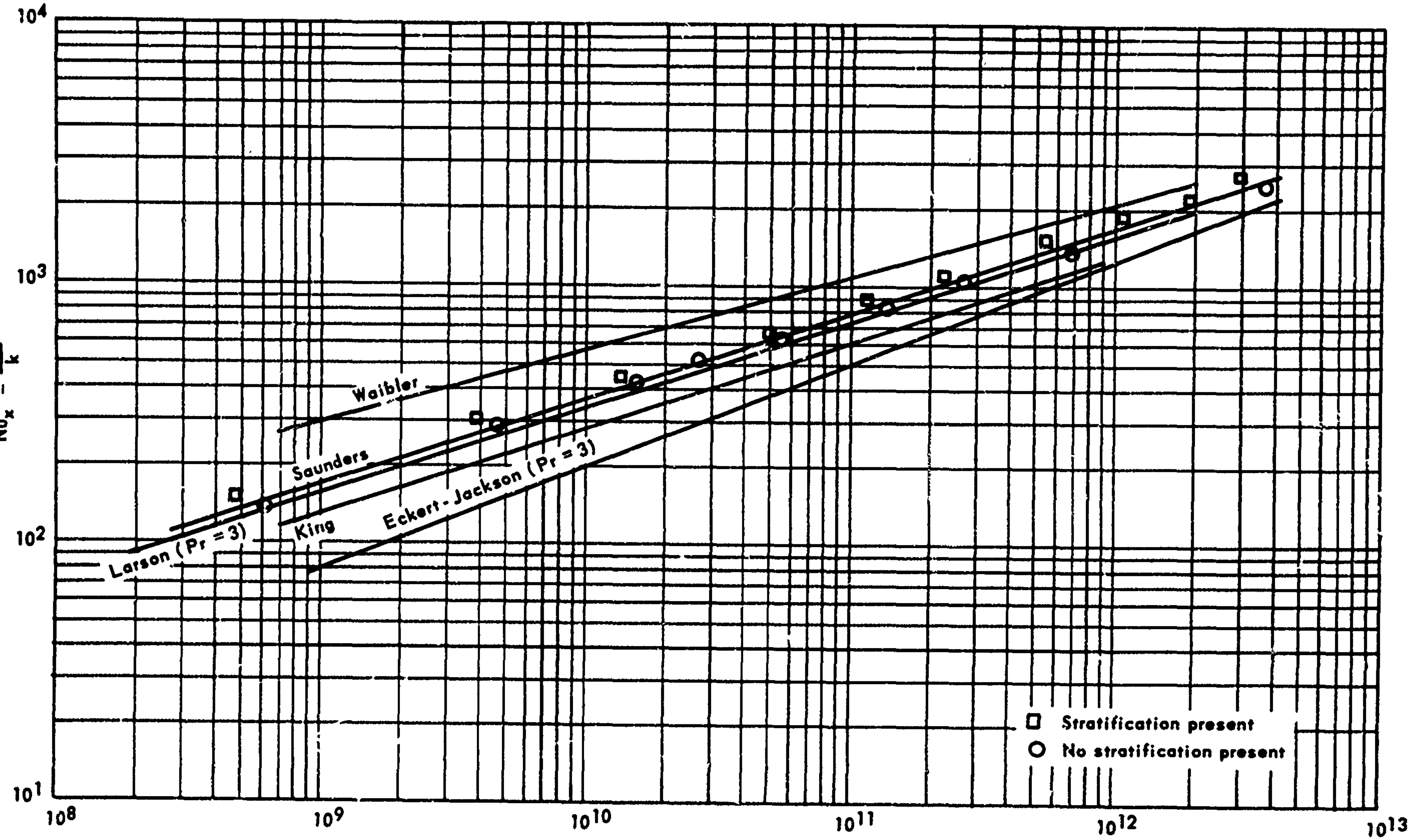


Figure 3. Turbulent natural-convection heat-transfer data for vertical plates or cylinders in water.



$Ra_x = X^3 \Delta T \left(\frac{g\beta}{\nu^2}\right)\left(\frac{C_p \mu}{k}\right)$

Figure 4. Natural-convection heat-transfer data for a vertical flat plate in water.

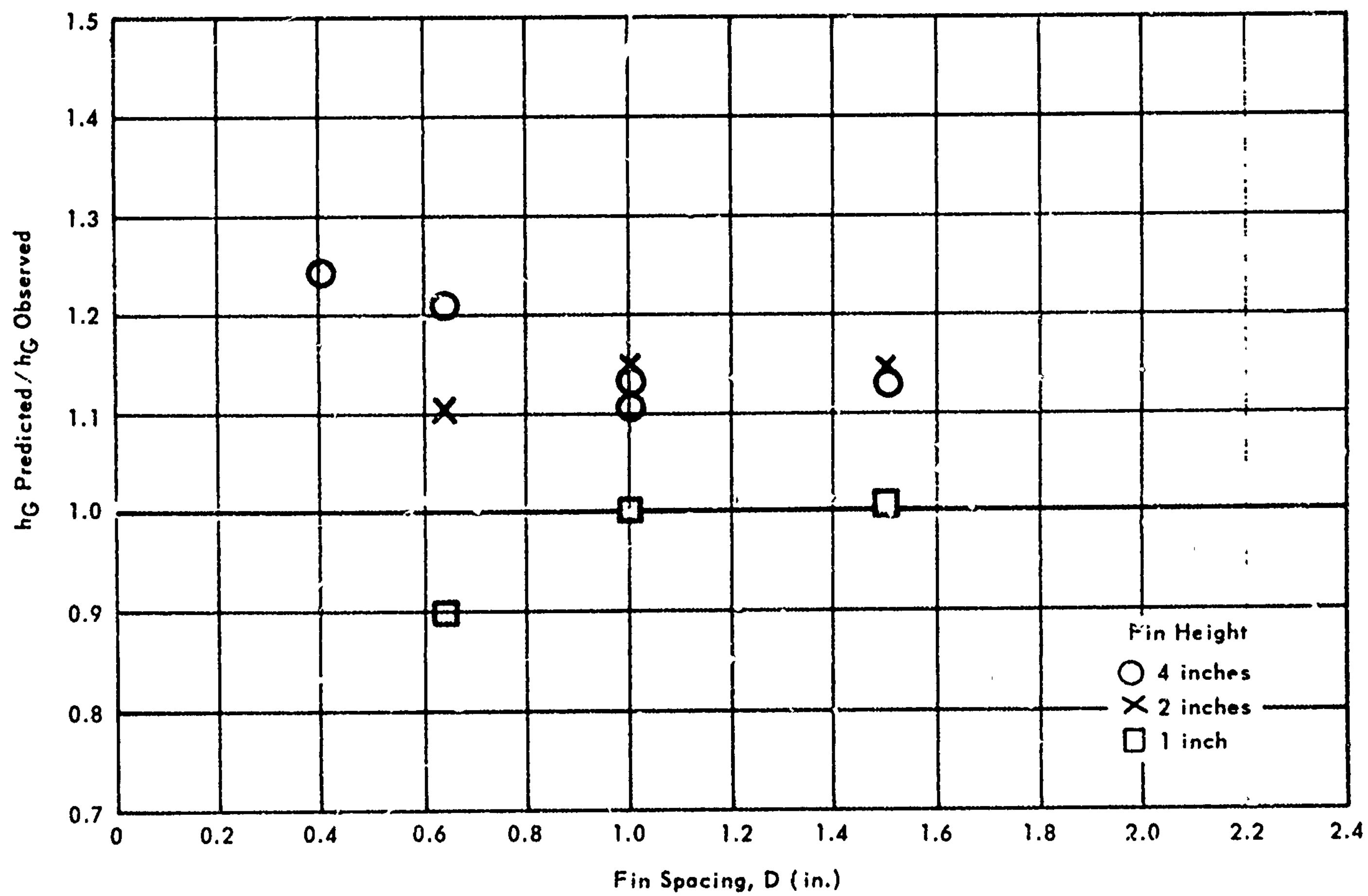


Figure 5. Comparison of observed and predicted gross heat-transfer coefficients in finned vertical plates.

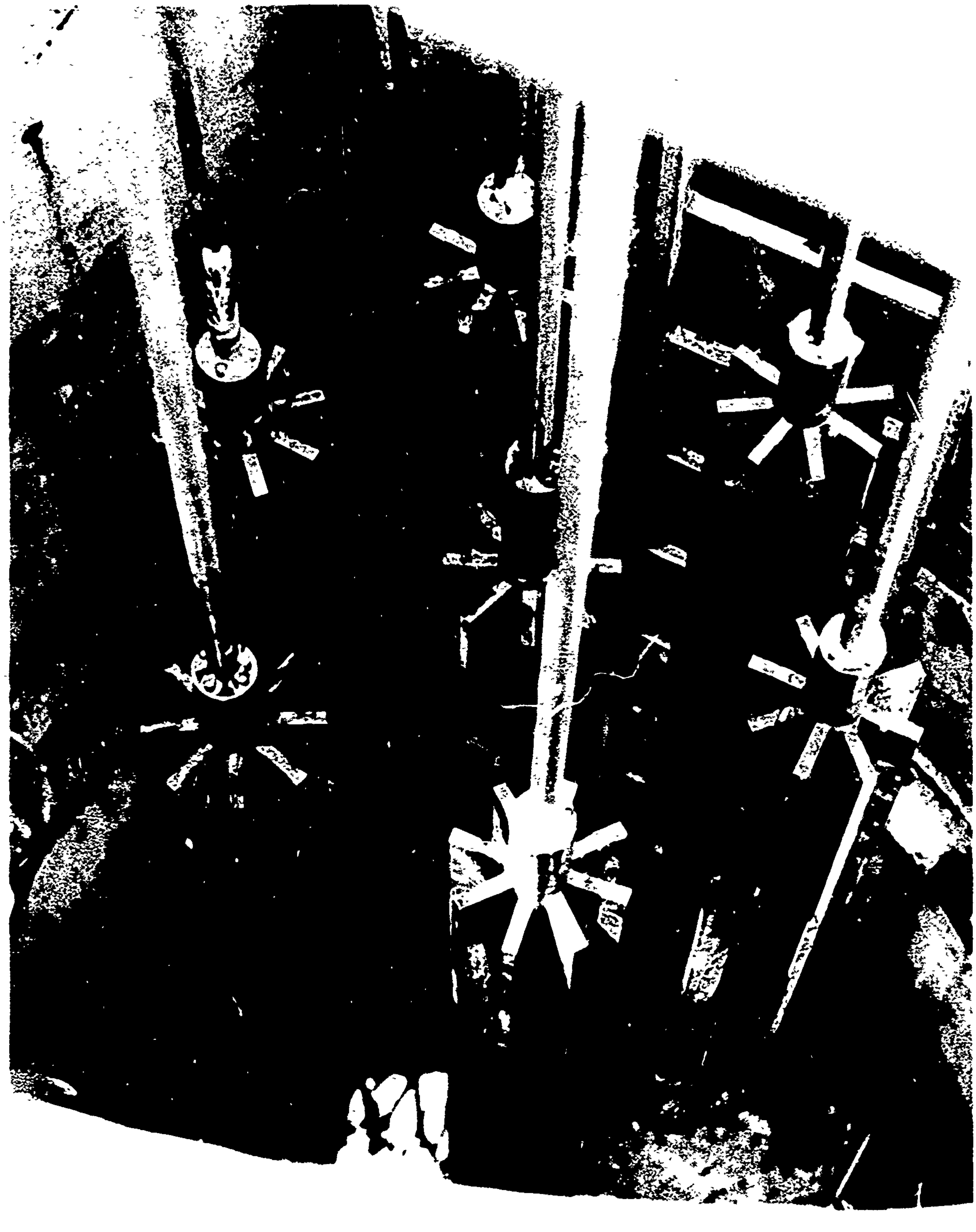


Figure 6. Cylindrical test unit.

Figure 7. Vertical finned cylindrical unit.

ADDITIONAL PROBLEMS SUGGESTED

For the case of the submerged nuclear reactor, operating at depths in the open ocean, most of the problems foreseen seem to have at least a plausible solution. In many cases the proposed and carefully considered solution has not been demonstrated, but reasonable engineering analysis has been made.

For less hazardous but equally novel power devices, now recognized to be within the range of reason, additional problems may exist. Two alternate systems suitable for generating smaller amounts of power, but still potentially in the kilowatt range, are apparently practical. Fuel cells and generators supplied with radioactive decay heat appear to fill this potential area of need. The particular problems foreseen with fuel cells are concerned with keeping the cells at the proper temperature, which varies with type. (See Allis-Chalmers, 1965.) It would always be desirable to operate at local pressure, if feasible. Inasmuch as most insulations available depend on finely subdivided air or vacuum spaces, an additional problem is introduced. However, the micro-beads usually used in syntactic foams are capable of furnishing insulation under widely varying pressures and probably can be formulated into a suitable rigid insulation.

With the availability of large quantities of Cobalt 60 as plutonium production is cut back and reactor capacity is released, decay heat becomes an attractive approach, especially in the deep ocean. The gamma rays from the decay source require heavy shielding, but the shipboard weight-handling equipment and the shielding capability of water reduce the hazards to a bare minimum. However, such a source cannot be turned off, so cooling must be provided to avoid melting of the fuel elements. Near the ocean's surface it is simple to obtain extremely high cooling rates by evaporation within closed passages. Depending upon the depth, it may or may not be practicable to depend on boiling. Other factors must be considered in the design, such as the allowable surface temperature of the circulating tubes, so boiling may in fact be practicable if appropriate materials and temperatures are selected.

The heat-transfer literature on boiling is far too vast to explore here, but boiling is perhaps the best understood of the various heat-transfer processes, largely through impetus from the nuclear reactor industry. Excellent treatments on the problems in the use of decay heat in large (5 to 50 kw) electrical generators for other recognized applications are available in Carney (1965), Savannah River Laboratory (1965), and Shivers (1965). With the single exception of possible complication with high saturation temperatures of water at great depths, the problems in the use of radioisotope decay heat in the ocean appear to be far simpler than those above sea level because of the certainty of an adequate supply of coolant.

SUGGESTED RESEARCH PROGRAM

Of the problems in producing and using power in the deep ocean, both old and new, the following appear to require further study or experimental verification of suggested engineering approaches:

1. Foundation design. The instability of the ocean's bottom in many areas may limit the placement of structures unless suitable flotation (or alternate) systems are both better defined and tried.

2. Long-time corrosion of selected prime metal surfaces. The tests known to date are short-life tests, owing to the high costs. Radioactive decay heat sources are suggested as a reasonable approach to supplying heat for the test units over long periods.

3. Fail-safe cooling of relatively large radioisotope-decay-heat-powered generators at great depths.

4. Integrated tests of methods of relocating in a remote ocean site. Many approaches which may act in concert have been developed, but a true trial is not known to have been made in very deep water in the open ocean.

5. Further studies and tests of cable-weight systems under dynamic conditions as found in open seas.

Appendix

SIGNIFICANT RECENT PROGRESS RELEVANT TO PLACEMENT AND MONITORING OF POWER SOURCES IN THE OCEAN

THE ENVIRONMENT

With the rapid increases in the volume of information on ocean research, it is impossible to state with confidence what is and is not known at a given time. However, source material readily available and in a form useful to engineers has recently been published. A convenient summary, with extensive references, is Chapter 2 of the U. S. Naval Civil Engineering Laboratory's Deep Ocean Engineering Manual (Tudor, 1964). Similar compilations are included in Braun (1965) and Bechtel (1965).

To repeat the earlier observations (Beck et al, 1964), the deep ocean's high pressure and copious cold waters appear to furnish a near-optimum environment for all power sources except those requiring air for combustion. At shallow sites even these might prove well adapted if properly packaged and if air and exhaust ducts are tolerated.

FOUNDATIONS

Smith (in Beck et al, 1964) describes highly unstable foundation conditions in the form of deep, soft sediments over a large portion of the ocean's bottom. The suggested solution involves buoyant "hulls" which would float on or in this ooze. These hulls have not been developed. Considerable testing of the physical properties of ocean-bottom specimens taken over wide areas now allow better definition of the problem. (See Smith, R. J., 1965.)

One approach would support the generator over a suitable anchor and a pressure buoy (Smith, J. E., 1965). This approach has been the subject of considerable investigation by Smith and Dantz (1963).

Another approach not described, but perhaps worth considering for small, portable power devices, would be the provision of a pressure-resistant buoy system with an overall small negative buoyancy. A diver might provide the small vertical force necessary to move the package by a sort of deep ocean "sky hook." Simple methods to adjust buoyancy might eliminate even the small forces necessary with a small negative buoyancy plus some of the forces necessary to pull an object from muds (Quirk, 1966). These forces are highly time-dependent, according to Quirk.

ANCHORAGES

For the most difficult case — a soft ocean bottom — foundations and anchorage are almost a common problem. The work of Smith and Stalcup (1965), combined with the pullout work of Quirk and Muga (1966), will allow a rational design approach, although much refinement will undoubtedly come in the future with application. it is probably entirely practical to design flotation foundations for stabilized bottom mounting of power packages, but reliable removal will depend upon the results of work such as that underway by Smith, Muga, and Quirk.

UNDERWATER VISION

The precise statement of the problems in long-range underwater vision (Hitchcock, in Beck et al, 1964) is probably still valid. However, Hitchcock (1966a) has further described the problem and the results of some experiments run since the earlier paper. The later paper discusses the possibilities of improving range of vision by using color or polarizing filters and off-axis illumination. While the title of Hitchcock's paper would indicate the study to be related to the use of television in harbors, television's value for any situation at any depth should not be discounted.

The possibility of using time-of-flight discrimination to increase the visibility range by eliminating scattered light is described by Hitchcock (1962), is mentioned briefly in Beck et al (1964), and is known to be a matter of current study by the Naval Ordnance Test Station, Pasadena, California. While the concept is interesting, the probable improvement is of the order of 50% in range, and the known approaches are very expensive. Probably more important, the equipment is rather complicated. A laser source of light is indicated for significant improvement. Nevertheless, seeing in murky bottom water is so important for security work that such approaches may be adopted at any cost and inconvenience. Unfortunately, no reliable report of progress on the current work is available.

NUCLEAR CONTAMINATION OF THE OCEANS

No recent work is known to have been done on the problem of nuclear contamination of the oceans, other than studies of world-wide fallout and waste discharged into estuaries, neither of which is closely related to the problems which might be created by activating the deep ocean's waters with a partially shielded reactor. The potential problems may very well be trivial, as the ocean has a prodigious capacity for diluting wastes. Until a great deal is known about circulation systems, it cannot categorically be stated that the problem will not have important ecological implications. A good review of some of the problems of atomic wastes in the sea is given by Wallin (1964).

LOCATION, RELOCATION, AND POSITION HOLDING

In spite of the considerable development in the field of precise navigation, little new information appears to be available to the mariner operating more than a few hundred miles from land. Here, he must obtain the best celestial fix possible and then work on local dead reckoning, buoys, or sonic bottom pingers for precise location. The devices for bottom-profile mapping are rapidly increasing in accuracy, but even a rapidly changing bottom profile becomes obscure if the water is deep. The comments of Beck et al have been well up-dated by Lee (1964), where the state of the art is well summarized. Additional information on anchoring and supporting of suitable sonic pingers is given by Smith (1964). In spite of the manifold problems (and lack of a suitable successful operational example to cite), it is probably true that with available methods, a location can be obtained within one-half to one mile in the open ocean, can be identified by placing an array of sonic buoys, and located and relocated precisely with the aid of submerged buoys or a suitable small search submarine. Such submarines are widely described by Terry (1964), Smith (1964), and Bechtel (1965).

CONNECTION TO POWER SOURCE

Once the undersea power source, controlling equipment, use device, and any storage batteries necessary are in proximity on the ocean bottom, connection would seem to be a simple task. It is probably not, however, unless the available connectors suitable for wet makeup under pressure are specially fitted for ease of handling. The necessary attachments would have to be designed for the particular manipulator on the service submarine. Self-powered hydraulic coupling devices, using the ocean's static hydraulic pressure as a motive source, would simplify the assembly.

While some development is indicated, the concepts are available, and the innovations are not of an order to make the function questionable.

SERVICE VEHICLES AND MANIPULATION

The success of the connection functions described above, the surveillance of the power-unit location, the monitoring of the source, etc., are uniquely dependent upon the use of a submarine or diving bell suitable for the pressure involved. There is considerable development in this area, and it is unquestionably true that if the necessary manipulatory functions are kept to a minimum and as simple as possible, a suitable vehicle can be rented or built. Some were considered earlier (Beck et al, 1964), and many more were described since: Terry (1964); Smith (1965); Bechtel (1965); and a very useful review, Interagency Committee on Oceanography (1965).

Manipulation is an advanced art, but must be specialized for the functions intended: for example, in connecting cables. Experience in doing useful work outside small submarines is accumulating rapidly, and the art is advancing rapidly without special attention to this intended application.

REACTOR MONITORING

Inasmuch as no reactors have been placed and monitored since the earlier study (Beck et al, 1964), the improvement in the state of the art must all be theoretical. Probably the most serious consideration of the field problem was made as part of a placement study (Bechtel, 1965). It was projected here that it would be feasible to approach, apply meter leads, etc., necessary to determine the condition and level of operation of the reactor, and make adjustments as necessary. In a sense, a submerged reactor can be considered a bare reactor with a variable thickness shield adjusted to suit the case. A submersible suitable to the purpose should prove extremely safe because of the available standoff distance, with the intervening space filled with water.

TEMPORARY POWER STORAGE

From the inception of the underwater nuclear power concept, it has been assumed that on-site power storage would be a desirable if not necessary adjunct to a reactor. The same would be true for other electrical sources, isolated or in the vicinity of manned structures. Operation of pingers used for location, telemetry of production-level information, illumination to assist in locating, recharging small submersible batteries, and powering of area-monitoring gear are some applications, in addition to the obvious need for intermittent storage of power to allow use of power well in excess of that being continuously generated ("peak shaving").

Chemical batteries still appear to be the only approach, and here the economical advantage of the lead-acid battery is so immense that it is doubtful if competitive chemical systems will be of immediate interest. A recent study incorporating much factual cost information on various chemical storage batteries is available (Allis-Chalmers, 1965). There has been some debate on the efficacy of lead-acid batteries at great depths, but there is every reason to believe that with suitable physical containment, lead-acid batteries can be effectively used at any depth, provided they are rated for the appropriate temperature and that provision is made for venting.

CONCLUSION

This appendix is neither meant to be exhaustive nor completely up to date. Except for very late developments, it is believed that it does furnish a fair picture of the state of the art in many fields of potential importance.

The bibliography lists a number of sources not directly discussed in the above text, but which will furnish leads on late research and additional reference material.

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13. ABSTRACT

Since the publication in 1964 of Techniques for Underwater Nuclear Power (NCEL TN-545), considerable research and development has been done which has changed the picture regarding the feasibility of using isolated reactors on the ocean bottom. This study considers in some detail the work on fouling, corrosion, and heat transfer accomplished by the C. F. Braun Company, Alhambra, California, under contract NBy-32274(AD-6[illegible] 175).

Also considered are additional problems which might be encountered in using radioisotope decay heat in large (multi-kilowatt) generators or fuel cells in the deep ocean environment.

A cursory up-dating of the known arts related in the earlier study is made, especially in referencing material which has recently become available.

Possible areas for further investigation are delineated. (U)

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